Acoustic Vibration Sensing and Control Mechanism for Boilers

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Abstract

Coal fired power plants are increasingly evolving and with the increase in population the plants now face high demand for electricity production. Coal fired plants are progressively looking for ways to improve the plant efficiency by using predictive maintenance methods which include acoustic cleaning. The research is mainly focused on Sasol Synfuels Power station which is situated in Secunda in the Mpumalanga province of South Africa. Sasol realized that the boilers are no longer performing as they should due to soot deposition on the boiler tubes, this has led to increased operating cost. This research reviews and investigates acoustics technology that can be used for boiler online monitoring and developing a method that can detect acoustic vibration induced by an acoustic horn. The theory is that acoustic horn produces sound energy that causes vibration on the boiler tubes which can be detected using acoustic vibration sensing devices and the signals can be converted into readable information through a closed loop control mechanism. Structural and modal analysis are performed which shows the stresses that the components experience under operation conditions. The modal tests have shown the maximum deformation where the components will experience the highest frequency resonance.

Keywords Acoustic Vibration; Control Mechanism; Boilers; Modal Analysis; Structural Analysis; Accelerometer; Sensors; Closed Loop Mechanism

1. Introduction

Coal fired plants generate electricity by burning coal in a boiler to create steam under pressure which is then directed into the turbine. The pressure of the steam causes the turbine to spin the generator which creates electricity (Authority, 2020). Part of the process of producing electricity involves a boiler, the most important part of the process. The design of a boiler ensures the plant's efficiency, therefore, it is imperative that the boiler performs at its best (Bethel Afework, 2018). When coal is burnt in the boiler the coal ash deposits on the wall surface. Ash deposition and slagging decreases the ability of the boiler to transfer heat by almost 30 to 60% and corrodes the boiler tubes which results in unscheduled shutdowns and decreased electricity generation capacity (Qinghai Li, 2016). Sasol Synfuels Power station situated in Secunda of the Mpumalanga province has a total of 17 boilers in which nine of them are in the eastern side and eight are in the western side. The ash acts as an insulation resulting in the use of more fuel needed to burn and reach the same temperature, this reduces the efficiency of the boiler. Currently they use a manual cleaning method where water is sprayed into the boiler (Shandu et al, 2021). This method is costly, and reduces the company's productivity, the water sprayed into the boiler causes corrosion and the boiler is constantly experiencing inconsistencies such as premature electric component failures (Shandu and Kallon, 2021). When this cleaning method occur, the boiler must be stopped so that the equipment can be moved to avoid damages. Acoustic cleaning devices uses sound vibration to prevent collection of coal ash. It uses sound waves to clean the surfaces without affecting the operation of the equipment. This device reduces boiler tube erosion, pressure drop, increase boiler life span and less maintenance will be required (Shandu et al, 2019). The aim of this research is to develop a sensor that will detect acoustic vibration induced in the boiler. The sensor needs to withstand the harsh conditions that the boiler imposes the sensor to, while measuring vibrations accurately as well as develop a control mechanism that will regulate the frequency of the acoustic device as signaled by the vibration sensor. Modal analysis used to determine the natural frequencies and mode shapes of a mechanical structure of a component under dynamic loading conditions. These are important parameters in the design structures for dynamic loading conditions.

2. Materials and Methods

The most common options in plants with PLC systems is using vibration sensor which outputs directly to the control system. The sensor must provide continuous trend data to make it easier to track changes in overall vibration levels and the method is cost effective. A display meter or an alarm module is good for plants without control systems in place, (Brannon, 2020). The acoustic vibration sensor is designed to receive an acoustic energy frequency of 75Hz from the acoustic horn (Shandu et al, 2018; Shandu, 2021). The sensor is required to operate without disrupting the operation of the boiler. The type of sensor used for this project is an accelerometer which measures vibrations, Figure 1. The sensors are designed to be fitted on the surfaces of the boiler tubes, a magnetic mounting that can be mounted on any metal surface will be used to mount the sensor as shown on Figure 2. The control system is wireless therefore it can be placed in a control room away from the boiler. The sensor is designed with a coil of 1.7mm pitch and height of 15mm, the hole is 6mm deep as seen in Figure 1.

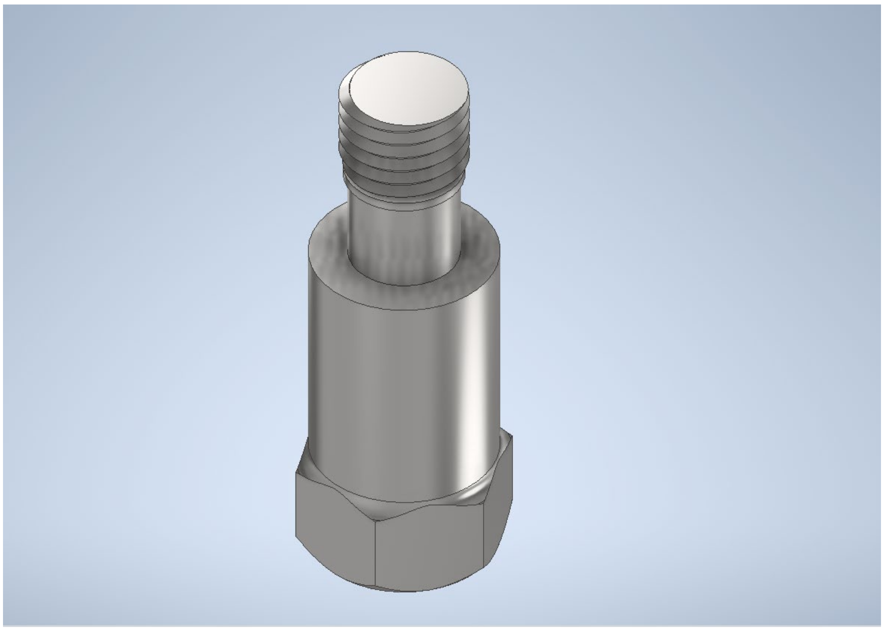


Figure 1: Conceptual design of an accelerometer sensor.

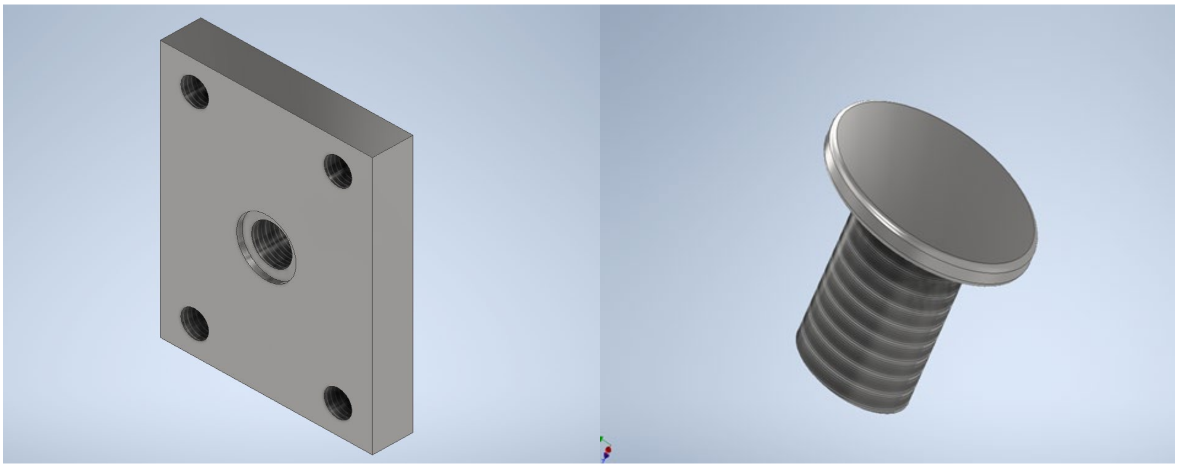


Figure 2: 3D mounting plate with a bolt.

3. Results

3.1 Calculations

According to the wave equation, motion equation, and gas state equation of sound propagation, the relationship between sound velocity and temperature is calculated

$$c = \sqrt{\frac{\gamma P}{\rho}}\sqrt{T} \tag{1}$$

Where c- is the sound velocity, γ- is the specific heat ratio, P- is the pressure, ρ- is the density, T- is the temperature. Under thermal environment, the stress-displacement relations can be expressed as in equation 2:

$$\sigma_x = \frac{E\alpha\Delta T}{1-v} \tag{2a}$$

$$\sigma_y = \frac{E\alpha\Delta T}{1-v} \tag{2b}$$

$$\tau_{xy} = 0 \tag{2c}$$

Where E-is Young's modulus, v- is Poisson's ratio, α- is the thermal expansion coefficient.

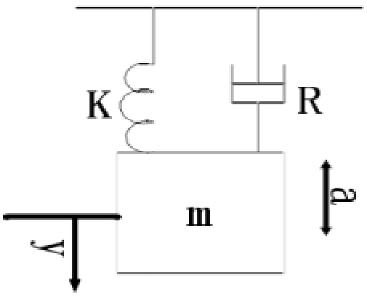


Figure 3: Basic mechanical model of vibration sensor (Guo, 2014).

Vibration differential equation is established from Figure 3 in accordance with Newton's second law:

$$m\frac{d^2y}{d^2t} + R\frac{dy}{dt} + ky = F(t) = ma(t) \tag{3}$$

$m\frac{d^2y}{d^2t}$ -The inertial force

$R\frac{dy}{dt}$ -Dynamic resistance

Where m is the mass of the vibrating object, R-is the dynamic damping coefficient, k-is the spring constant, a-is the input acceleration, y is the displacement of the mass which is relative to the housing. F(t) shows a support beam elastic force. The equation (3) is made for the Laplace transform under zero initial conditions, to obtain:

$$m.s^2Y(s) + RsY(s) + KY(s) = mA(s) \tag{4}$$

Therefore, the transfer function may be determined using the following:

$$H(s) = \frac{x(s)}{a(s)} = \frac{m}{ms^2+cs+k} = \frac{1}{s^2+s\left(\omega_r/_Q\right)+\omega^2{}_r} = \frac{1}{s^2+2s\zeta\omega_r+\omega^2{}_r} \tag{5}$$

Where $\omega_r = \sqrt{\frac{k}{m}}$, is the natural frequency of the vibration mass,

$Q = \sqrt{km}/\text{c} = \omega_r m/c$ is the quality factors,

$\zeta = 0.5/Q$ is the dumping factor.

3.1 Structural analysis

Structural analysis aid to determine the structural aspect of the components.

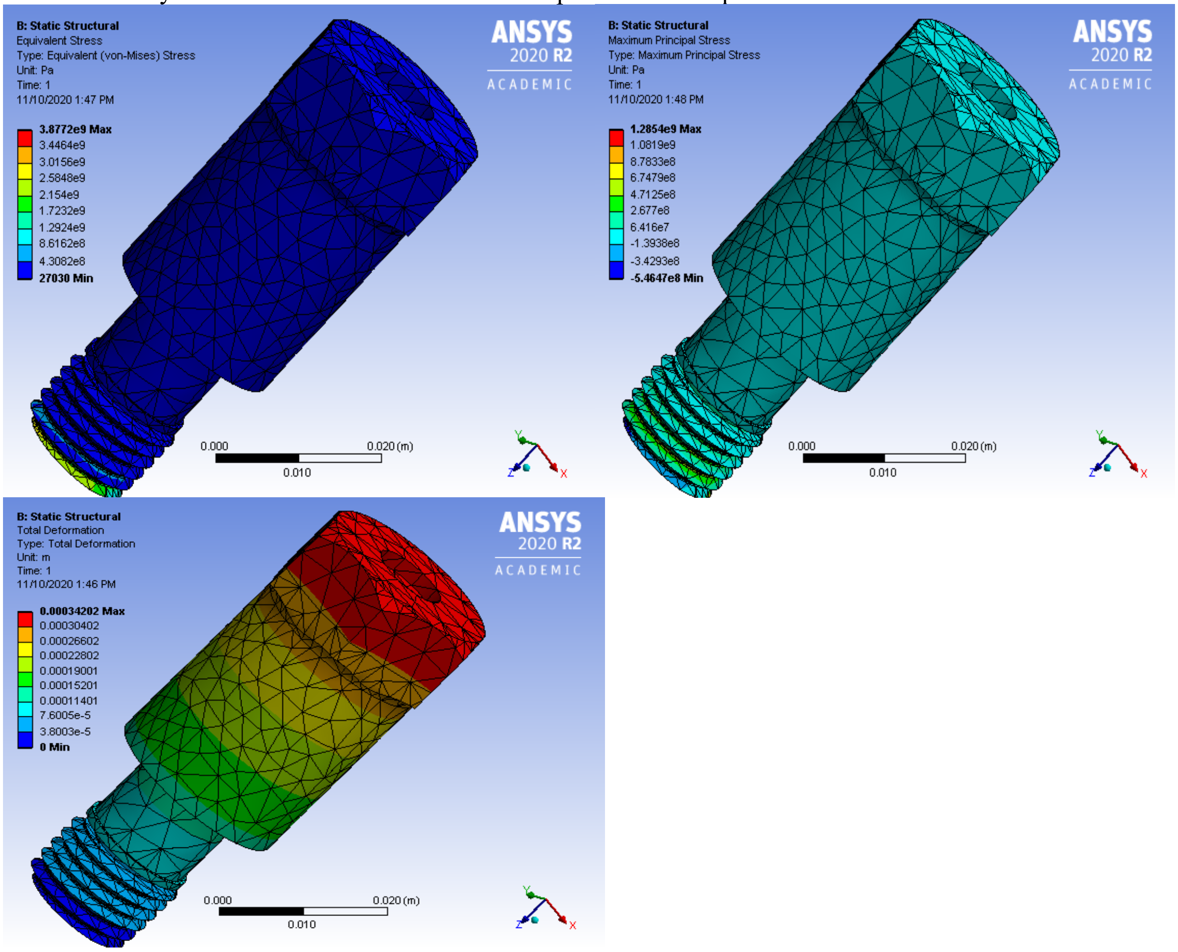


Figure 4: Structural analysis of accelerometer

Table 1: Mesh details for structural analysis

Defeature Size	Default
Transition	Fast
Span Angle Center	Coarse
Initial Size Seed	Assembly
Bounding Box Diagonal	6.7168e-002 m
Average Surface Area	1.365e-004 m^2
Minimum Edge Length	5.7225e-004 m
Quality	
Target Quality	Default (0.050000)
Smoothing	Medium
Mesh Metric	None
Statistics	

Nodes	9283
Elements	5112
Element type	Tet10

Table 2: Simulation results

Scope			
Scoping method	Geometry selection		
Geometry	All bodies		
Type	Total deformation	Von-mises stress	Maximum principle stress
Results			
Minimum	0	27030 Pa	-5.4647×10^{8}
Maximum	3.4202×10^{-4}	3.8772×10^{9}	1.2854×10^{9}
Average	1.4686×10^{-4}	1.9605×10^{8}	7.0428×10^{7}
Occurs	**Acoustic vibration sensor**		

Table 3: Material properties from ANSYS software

Strength coefficient Pa	**Strength exponent**	**Ductility coefficient**	**Ductility exponent**	**Cyclic strength coefficient Pa**	**Cyclic strain hardening exponent**
9.2×10^{8}	-0.106	0.213	-0.47	1×10^{9}	0.2

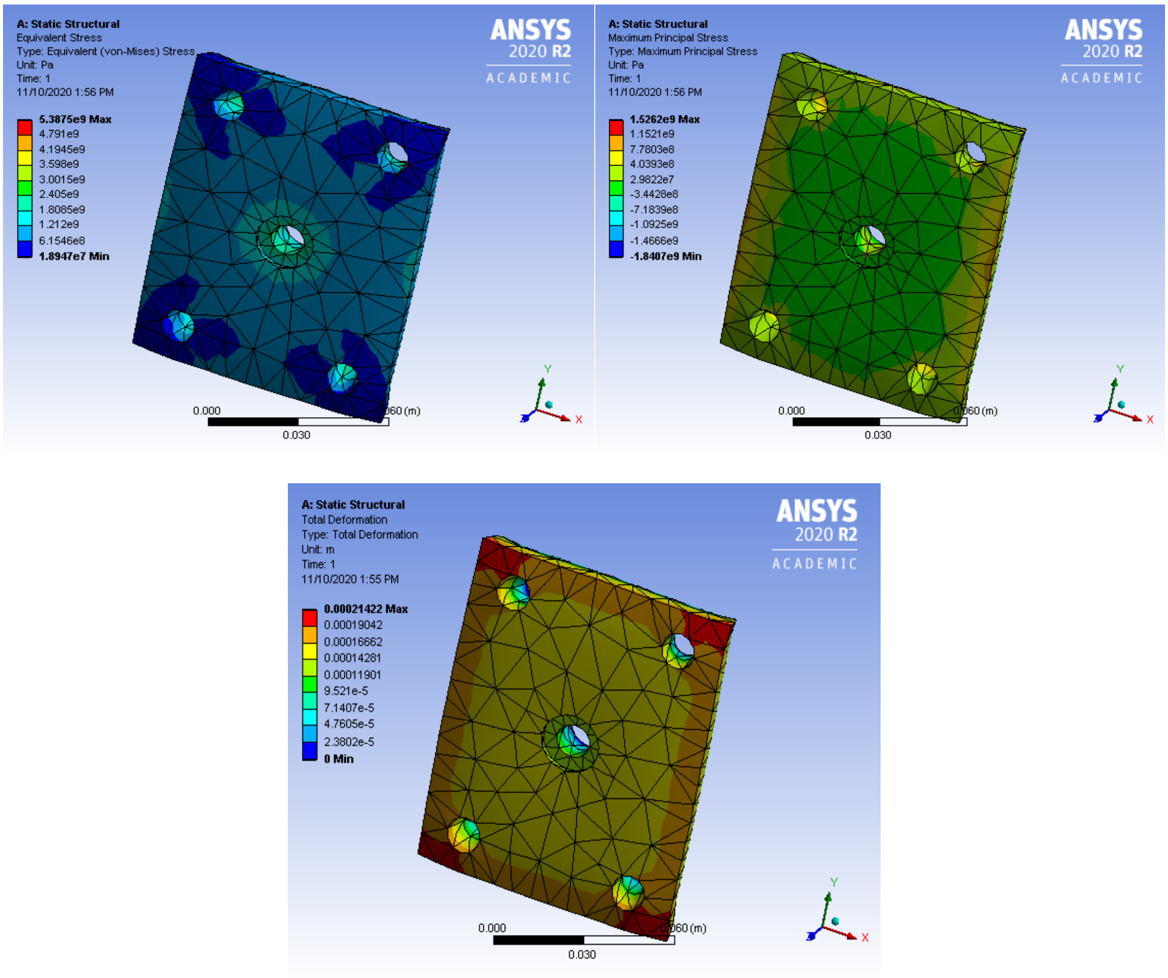


Figure 5: Structural analysis of mounting plate

Table 4: Simulation results

Scope			
Scoping method	**Geometry selection**		
Geometry	**All bodies**		
Type	**Total deformation**	**Von-mises stress**	**Maximum principle stress**
Results			
Minimum	0	-1.8407$\times 10^9$ Pa	1.8947×10^7
Maximum	2.1422×10^{-4}	1.5262×10^9	5.3875×10^9
Average	9.2806×10^{-5}	1.6779×10^8	1.351×10^9
Occurs	**Mounting plate**		

Table 5: Material properties

Material	Steel
Density	7850 kg m^-3
Coefficient of Thermal Expansion	1.2×10^{-5} C^-1
Specific Heat	434 J kg^-1 C^-1
Thermal Conductivity	60.5 W m^-1 C^-1
Resistivity	1.7e-007ohm m

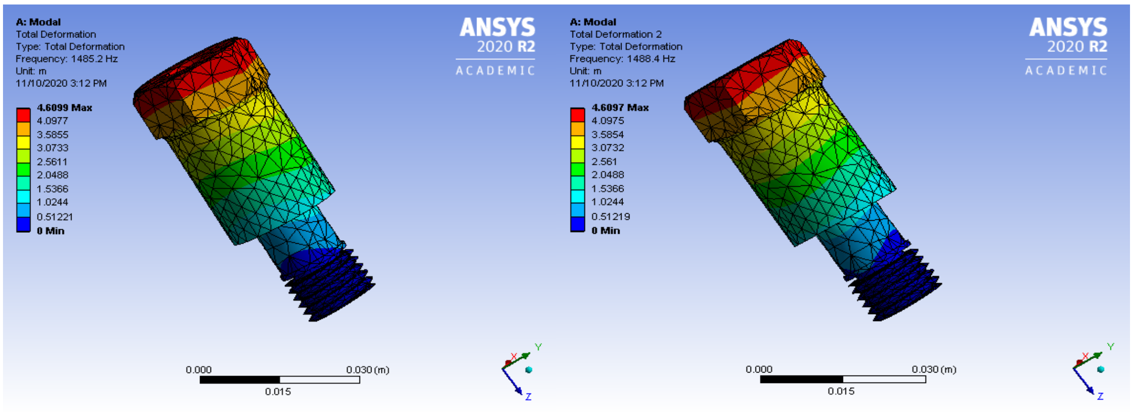
Table 6: Material properties

Young's Modulus Pa	**Poisson's Ratio**	**Bulk Modulus Pa**	**Shear Modulus Pa**	**Temperature C**
2×10^{11}	0.3	1.6667×10^{11}	7.6923×10^{10}	22

Table 1 shows the mesh properties used in the structural analysis. It was determined that the mounting plate will deflect by 0.00034202m under 552KPa pressure. The sensor will experience a stress of 267 MPa, Figure 4, Tables 2 and 3. The mounting plate will experience stress of 29.8 MPa under the boiler thermal conditions and an equivalent stress of 430 MPa, Figure 5, Tables 4 and 5. The acoustic sensing system consist of pressure sensor, thickness sensor, acoustic vibration sensor, and temperature sensor. The sensors sense a maximum frequency of 75Hz from the acoustic horn. The material that was selected for the design was carbon steel, which is capable of withstanding harsh temperature conditions of up to 1540 ℃, Table 6 [Shandu and Kallon, 2021].

3.2 Modal Analysis

Modal analysis was performed in ANSYS software, the 3D solid models were developed in AutoCAD then converted to STEP files which allowed the ANSYS software to read them.



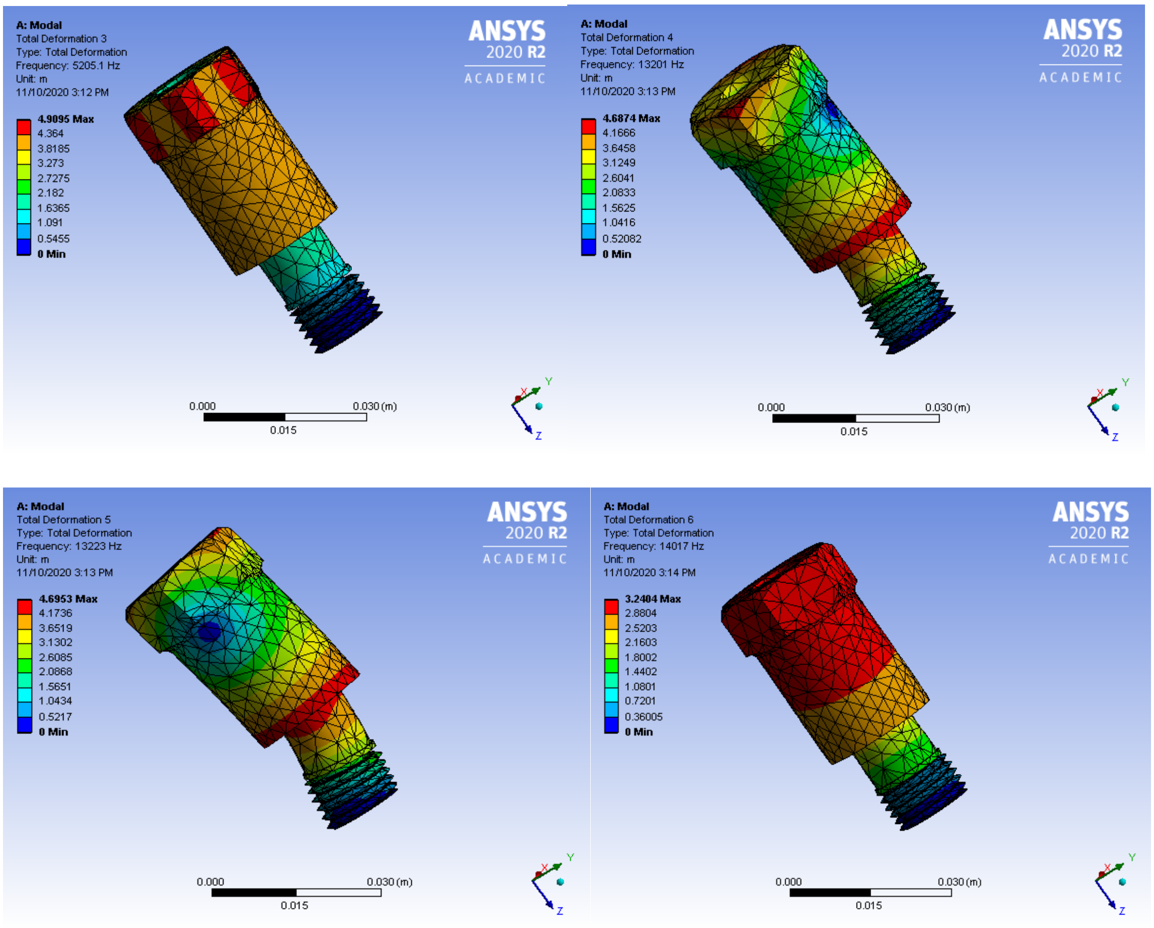


Figure 6: Modal simulation results on accelerometer model

Table 7 illustrates the populated results from modal analysis (Figure 6) on ANSYS software, showing the maximum deformation that the sensor will experience at each mode frequency. The results are graphically represented on Figure 7, which indicates the natural frequency increases when the maximum deflection decreases. Table 8 illustrates the populated results from modal analysis (Figure 8) on ANSYS software, showing the maximum deformation that the mounting plate will experience at each mode frequency. The results are graphically represented on Figure 9, which indicates the natural frequency increases when the maximum deflection decreases.

Table 7: ANSYS generated results

Mode	**Frequency (Hz)**	**Maximum deformation (m)**
1	1485.2	4.6099
2	1488.4	4.6097
3	5205.1	4.9095
4	13201	4.6874
5	13223	4.6953
6	14017	3.2404

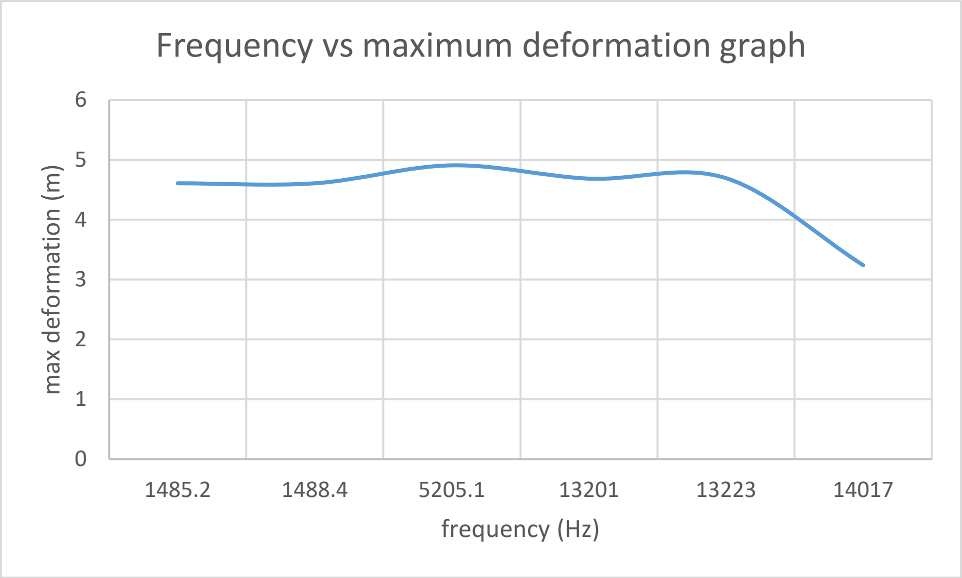
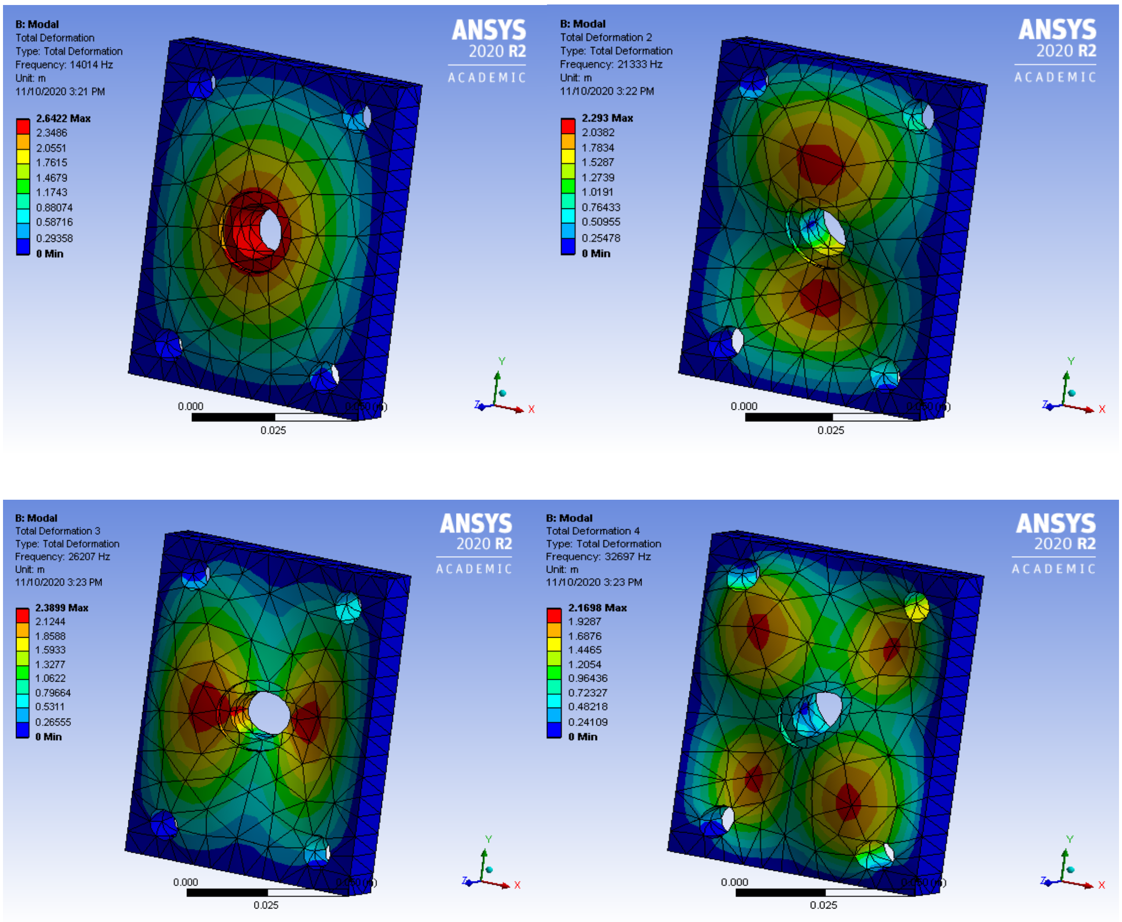


Figure 7: Graphical representation of ANSYS generated results



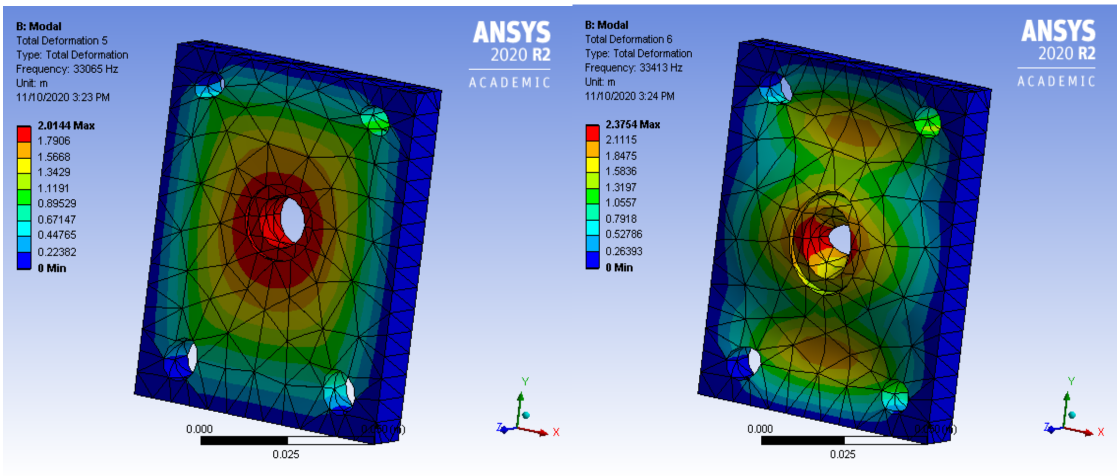


Figure 8: Mounting plate modal analysis results

Table 8: ANSYS generated results

Mode	**Frequency (Hz)**	**Maximum deformation(m)**
1	14014	2.6422
2	21333	2.293
3	26207	2.3899
4	32697	2.1698
5	33065	2.0144
6	33413	2.3754

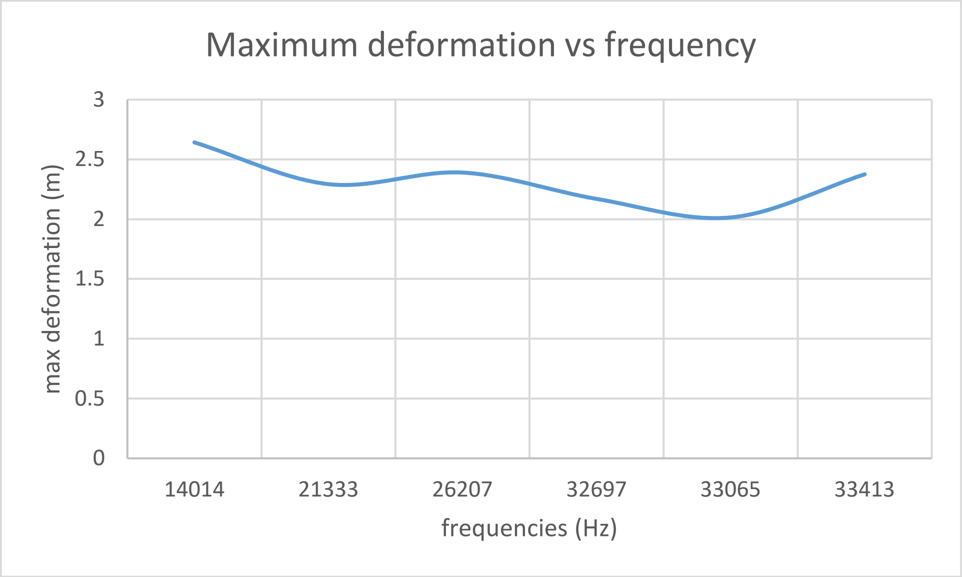


Figure 9 Graphical representation of ANSYS generated results

4. Discussion

It was determined that the mounting plate will deflect by 0.00034202m under 552KPa pressure. The sensor will experience the stress of 267 MPa. The mounting plate will experience stress of 29.8 MPa under the boiler thermal conditions and an equivalent stress of 430 MPa. The acoustic sensing system will consist of pressure sensor, thickness sensor, acoustic vibration sensor, and temperature sensor. The sensors will sense a maximum frequency of 75Hz from the acoustic horn. The material that was selected for the design was carbon steel, which capable of withstanding harsh temperature conditions of up to 1540 ℃.

The modal simulation showed where the components will experience the maximum frequency (resonance) which is shown by having the maximum deformation. Theoretically this is in the vertical y- direction which indicates that the design is weakest at that point, this makes sense because the moment of inertia is lowest in the vertical y-direction. Table 6 and Table 7 shows the maximum deformation of the components at different frequencies. The components that are critical to the system included the mounting plates and sensors, they were selected since they interact directly with the boiler and the acoustic horn. The sensor receives a high level of stress due to the frequency it receives from the acoustic horn. Both the mounting plate and sensor experience the same operating conditions of the boiler. Therefore, they were simulated under the same environmental conditions.

5. Conclusions

The approach to this research was to do a literature review where different articles were studied on similar projects to determine the feasibility of this project. In addition to literature review, data collection questions were compiled and used to interview one of Sasol's artisans. The selected sensor for this project is an accelerometer which is widely used for vibration detection purposes. For monitoring systems, soot thickness sensor, temperature sensor and pressure sensor will be incorporated. The sensors will be mounted on the boiler tubes using a magnetic mounting plate. A closed loop control mechanism for this purpose was recommended because it requires little to no human interaction, the system should monitor without interrupting the boiler operation. The simulations done in this project allows us to determine the areas of the design that needs to be improved.

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